UCRL- 91682
PREPRINT

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This paper was prepared for submittal to
IEEE Transactions on Nuclear Science
October 30 - November 1, 1984
Orlando, Florida

October, 1984

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Abstract

Uncertainties in estimating the potential health impact of a given radiation exposure include instrument measurement error in determining exposure and difficulty in relating this exposure to an effective dose value. Instrument error can be due to design or manufacturing deficiencies, limitations of the sensing element used, and calibration and maintenance of the instrument. This paper evaluates the errors which can be introduced by design deficiencies and limitations of the sensing element for a wide variety of commonly used survey instruments. The results indicate little difference among sensing element choice for general survey work, with variations among specific instrument designs being the major factor. Ion chamber instruments tend to be the best for all around use, while scintillator-based units should not be used where accurate measurements are required. The need to properly calibrate and maintain an instrument appears to be the most important factor in instrument accuracy.

Problems of Real World Measurements

Actual dosimetric applications of health physics survey instruments involve making estimates of relative health risks under conditions often significantly different than that found in theoretical models and in the calibration laboratory. An earlier publication [1] dealt with this problem and consideration was given to different exposure geometries and the difference in radiosensitivity of different body organs.

In actual practice, the radiation fields are almost never monoenergetic. Even in those rare cases where a monoenergetic source may be used, shielding is also employed which creates a lower energy scatter spectrum. In reactors and nuclear processing plants, multiple radionuclides are usually involved. As a result, radiation fields usually involve a spectrum of energies rather than a discreet energy. Radiation instrumentation, on the other hand, is usually calibrated with monoenergetic sources so that its response is known as a function of energy rather than as a response to multiple spectral inputs. It should be noted, however, that, since there are an almost infinite variety of various spectral combinations, it has not been practical to try to calibrate instruments in terms of such a series of "standard" spectra.

A second complication is that, in practice, radiation fields which do not approximate a point source or a parallel beam flux are often encountered. These omnidirectional fields can result from multiple sources and from scatter from massive structures and shielding within the vicinity of the source or exposed individual. Even for those cases involving parallel beam exposure, the net effect to the individual may be better approximated by a distributed source geometry since the individual will likely move and rotate in the radiation field.

Realistic Dose Estimates

The two principal factors to consider in estimating real world instrument performance are those of energy spectrum distribution and incident direction of the radiation. In the case of distributed energy, it is possible to consider the response of the instrument to different types of spectra which are representative of the range of spectra which are normally encountered. This can be readily done computationally provided the monoenergetic response of the instrument and the relative energy distribution of the spectrum being considered are known.

The problem of the effect of different exposure geometries is best considered by using the different conversion factors discussed elsewhere [1,2] which relate the effective dose under these different exposure conditions to the exposure from a parallel beam source as measured at a point in space by the instrument. Under these conditions, the measured instrument response for a parallel source can be used in this evaluation.

Comparison Approach for Instruments

Measurement of the instrument response to a point source (which approximates a parallel beam radiation field) has been made at Lawrence Livermore National Laboratory (LLNL) for representative instruments from the major classes of instruments as categorized by the type of detection element used in those instruments. In addition to the LLNL data, additional data from the published literature have been reviewed and included in this analysis [3-7]. This data has been converted to a form convenient for computational comparison of the different instruments for different incident spectra and dose conversion factors.

In order to evaluate the response of these instruments for different energy spectral distributions, several "standard" energy spectra were selected. The principal source of these spectra is from a study recently completed by P. L. Roberson at Battelle Pacific Northwest Laboratories for the NRC [8]. These spectra were taken for numerous locations within operating and shut down nuclear power plants and represent the types of spectra to which individuals may be exposed.

The specific spectra considered are as shown in Table 1.

Table 1.

#1	Low Energy	^{133}Xe Plume.
#2	High Energy Spectrum	Turbine floor 272 near viewing gallery. Operating BWR, Location A, Site O.
#3	Medium Energy Spectrum	Reactor Vessel Sampling Station. Operating BWR, Location J, Site O.
#4	Instrument Comparison	"Unity" spectrum.

In addition to the reactor facility spectra, a low-energy spectrum characteristic of a ^{133}Xe plume from a reactor was considered as being representative of the type of low energy spectrum which may be encountered in normal gamma ray survey work. Finally, a "unity" spectrum was used to evaluate instrument effects independent of spectral bias.

The response of the different instruments to the different spectra for the different operational quantities can be performed in a straightforward fashion using the expression:

$$\text{Relative Response} = \frac{\text{Instrument Reading}}{\text{True Dose Rate}}$$

$$= \frac{\sum_{i=1}^{n} \Delta E_i \; S_i \; R_i \; J_i}{\sum_{i=1}^{n} \Delta E_i \; S_i \; CX_i \; K_i}$$

where

ΔE_i = energy increment

S_i = spectral weighting over ΔE_i

R_i = relative instrument response at E_i

$CX_i = \frac{\text{Rems}}{\text{Roentgen}}$ conversion factor at E_i

J_i = Measured units per unit exposure rate at E_i

K_i = Radiation exposure rate in $\frac{\text{Roentgens}}{\text{Unit Flux}}$ at E_i

These calculations are done by first integrating the spectrally weighted instrument response. Then the actual spectrally weighted operational quantity of interest (such as effective dose at 1 mg/cm^2) is calculated. The ratio of these two quantities then gives the accuracy with which a given instrument is able to measure a given operational quantity when used in a given radiation field corresponding to one of the "standard" energy spectra. Values greater than unity would indicate that the instrument is over responding, while values less than unity would indicate that the instrument is under estimating the operational quantity of interest.

Instrument Comparisons

Estimates of instrument measurement accuracy and an assessment of the errors in measuring the different operational quantities have been performed for the following situations:

Case a. Instrument variations only for evaluating exposure rate without spectral weighting or correction for operational quantities.

Case b. Instrument variations only for evaluating exposure rate but weighted by the instrument response to various spectra.

Case c. Errors introduced when measurements are made for the different spectra if the assumption is made that dose = exposure (rems = R). The operational quantity desired is dose at 1000 mg/cm^2.

Case d. Instrument variations for evaluating dose at 1000 mg/cm^2 for the different spectral conversion factors are applied to the readings and this is the operational quantity that is desired.

Case e. Errors introduced in evaluating the dose rate under different spectral conditions by using the conversion factors for effective dose at 1000 mg/cm^2 when the radiation is omnidirectional and the effective dose rate is calculated based on the ICRP26 weighting of the different organ doses.

Case f. Errors introduced in evaluating the dose rate under different spectral conditions if the assumption is made that dose = exposure (rems = R) when the radiation is omnidirectional and the effective dose rate is calculated based on the ICRP26 weighting of the different organ doses.

Case g. Errors introduced in evaluating the dose rate under different spectral conditions by using the conversion factors for peak dose at 7 mg/cm^2 (which is close to the dose equivalent index) when, in fact, the proper operational quantity is dose at 1000 mg/cm^2.

Based on these cases, 99 instruments were compared. Instrument types included those based on scintillators, ion chambers, proportional counters, scintillators, and semiconductor detectors. In addition, three thermoluminescent dosimeters (TLD-LiF) were evaluated for comparison.

Instrumental differences were first compared based on the "Case a" criteria above and the results are shown in Table 2.

Table 2.

Summary of Instrument Response Accuracy for Different Survey Instruments Assuming a Unity Energy Spectrum and Rem = R (Case a).

Instrument Type	Number of Instruments	Relative Response Accuracy Low	High	Average
GM Counters	44	0.312	1.46	1.03 ± 0.19
Ion Chambers	45	0.689	1.58	1.07 ± 0.25
Proportional Counters	2	--	--	1.05
Scintillators	3	0.302	0.400	--
Semiconductors	2	0.98	0.99	--
TLDs (LiF)	3	0.99	1.35	--

As can be seen, all of the survey meters except those based on scintillators had an average response which ranged between 0.99 and 1.07. In the case of GM counters and ion chambers, sufficient data exists to determine averages and standard deviations as indicated. On the basis of the existing data, there does not appear to be a statistically significant difference in the accuracy of making dose rate measurements by using either an instrument based on a GM counter or one based on an ion chamber. In practice, there is a greater difference between different instruments within a given category than between instrument categories.

The lowest instrument response in the GM counter category was a Phillips X-Ray Monitor which has a maximum advertised operating energy of 80 keV and perhaps should not have been considered in this comparison. The next lowest instrument response was a Wallac Automatic Alarm Dosimeter--RAD 21 which had an accuracy of 0.797. This compares favorably with the lowest responding ion chamber instrument.

Many of the GM counter and ion chamber instruments have a movable shield which is used for discrimination against beta rays. An analysis has been made of the effect of the movable shield or cap on the overall response of instruments for which measurements have been made. Table 3 shows the results of these differences. As can be seen, there is little difference between instrument response with or without the shield for the unity spectrum, though the GM counter-based instrument response was about 5 percent higher without the shield.

Table 3.

Effect of Beta Shield on Instrument Accuracy for Different Spectral Inputs Assuming Rem = R (Case a).

Instrument	Relative Response Accuracy: Unity Spectrum	Low Energy Spectrum #1	High Energy Spectrum #2
GM Counters			
Shield Open	1.09 ± 0.21	2.53 ± 1.23	1.14 ± 0.22
Shield Closed	1.04 ± 0.14	1.07 ± 0.37	1.05 ± 0.14
Ion Chambers			
Shield Open	1.06 ± 0.29	1.62 ± 0.97	1.09 ± 0.38
Shield Closed	1.07 ± 0.20	1.16 ± 0.60	1.12 ± 0.23

The effect of the shield becomes more pronounced when the energy spectrum being monitored favors either the low- or high-energy spectrum. As can be seen, GM counters with the shield open have a significantly higher response (2.53 vs. 1.07) at lower energies. Ion chambers also have a somewhat enhanced response (1.62 vs. 1.16) but less than the GM counters. At high energies, the difference is much less (1.14 vs. 1.05) for the GM counters and is actually reversed (1.09 vs. 1.12) for the ion chambers, presumably due to reduced build-up in the ion chamber without the shield in place.

As can be seen in Table 3, spectral weighting can have a significant influence on the response of the different instruments. For this reason, instrument accuracies were evaluated for the three different spectra described earlier in this report. Table 4 shows the summary of the response variations for the different instrument types, again assuming that rem = R.

As expected, the most significant variations were for the low-energy spectrum where window and energy cutoff effects are most pronounced. By instrument type, the ion chambers showed the most uniform overall response under different spectral conditions. The GM counters showed the characteristic over response at low energies which might be expected.

The scintillator-based instruments showed the largest range of response, especially at lower energies where one instrument over responds by 68.4X for the ^{133}Xe plume spectrum. Under response at high energies, which might be expected to be significant for the scintillators based on their monoenergetic response at higher energies, was not significant. This is due to the fact that the high energy spectrum used has significant low-energy components which largely balances out the instrument response.

Up until now, we have been evaluating instruments on the basis that rems = R in estimating dose (rems) based on instrument readings which are usually in units of exposure (R). 10CFR20 [2] defines conversion factors which are energy dependent for making corrections to instrument readings for the determination of dose, and we have evaluated response using those factors. In addition, we have considered additional conversion factors discussed in an earlier publication [1] which may give an effective dose which is more directly proportional to health risk effects. These different conversion factors were considered as

Table 4.

Instrument Accuracy for the Measurement of Different Ranges of Spectral Energy for the Different Instrument Categories Assuming Rem = R (Case b).

Instrument	Relative Response Accuracy: Low	High	Average
GM Counter			
Low Energy (Spectrum 1)	0.339	8.05	1.99 ± 1.67
High Energy (Spectrum 2)	0.301	1.49	1.06 ± 0.19
Medium Energy (Spectrum 3)	0.298	1.42	--
Ion Chamber			
Low Energy (Spectrum 1)	0.409	3.69	1.19 ± 0.66
High Energy (Spectrum 2)	0.720	1.82	1.12 ± 0.39
Medium Energy (Spectrum 3)	0.740	1.82	--
Proportional Counters			
Low Energy (Spectrum 1)	1.29	4.94	--
High Energy (Spectrum 2)	1.06	1.11	--
Medium Energy (Spectrum 3)	1.06	1.10	--
Scintillators			
Low Energy (Spectrum 1)	8.79	68.4	--
High Energy (Spectrum 2)	0.650	1.52	--
Medium Energy (Spectrum 3)	0.854	1.58	--
Semiconductors			
Low Energy (Spectrum 1)	0.899	27.18	--
High Energy (Spectrum 2)	1.02	1.41	--
TLD			
Low Energy (Spectrum 1)	0.99	1.34	--
High Energy (Spectrum 2)	0.99	1.34	--

Cases c through g above, and the calculated instrument responses for each of these cases has been performed.

This data has been condensed into Table 5 for the GM counters and ion chambers. The values indicated show the range between the lowest and the highest responses for each instrument type and energy spectrum. Of these, Cases e and f show the largest variations with the main discrepancy occurring at lower energies. This occurs since the conversion factor has the greatest difference, and instrument effects are most pronounced in this energy range.

The actual variation between the different measurement assumptions is somewhat clouded in Table 5, however, since a large number of instruments was considered resulting in a significant range in values. Table 6 shows the variations in response for the Victoreen 471 whose energy response as measured at LLNL was found to be relatively flat with energy. Also shown in Table 6 are the response variations for representative instruments from the other instrument categories. Note the particularly good response of the diamond detector and the relatively nonuniform response of the scintillator.

Case c and Case d are the two most common measurement modes of assuming that rem = R (Case c) or correcting using C_x for dose at 1 mg/cm^2 (Case d) when the proper operational quantity is dose at 1 mg/cm^2. As expected, the only significant difference occurs at low energies, with the exception of the scintillator which also shows a significant change at higher energies due to its strong weighting toward a low-energy response. In general, instrument variations are much larger than the 3-4 percent change seen for most spectra by making the corrections for dose at 1 mg/cm^2. Thus, if corrections are going to be used with any meaning, great care needs to be exercised in instrument selection and calibration.

Case c considers the possibility that health risks may be proportional to the ICRP26 weighted conversion factors. If this is the case, then errors on the order of 3x at low energy and 1.6x at medium and high energy are being introduced by using the 10CFR20 conversion factors for dose at 1 gm/cm^2, and higher still if the assumption that rem = R is made. This is clearly a more significant factor than making the C_x corrections for dose at 1 gm/cm^2, but involves the determination of whether the ICRP26 weighted C_x factor is, in fact, the correct health risk factor.

It should be noted that the observed variations in instrument response noted in Table 4 for the different categories of instruments and even within instrument categories significantly exceed the factors involved in the different measurement assumptions. This further emphasizes that if care is not taken in the selection and calibration of an instrument, there is no point in worrying about which conversion factor to use.

Conclusion

The results of this study indicate several factors of importance to health physics measurements. These are:

a) There is not a significant difference between GM counter-based instruments and ion chamber-based instruments for general purpose survey work when applied to real world spectra, provided the instruments are properly calibrated and maintained.

b) More demanding applications, such as low energy survey work, are better served with an ion chamber instrument.

c) Instrument variations tend to far outweigh correction factor effects for dose at 1 gm/cm^2 unless great care is taken in instrument selection and calibration.

d) Selection of an appropriate conversion factor to represent possible health risk effects can result in variations in readings from 3x at low energies to 1.6x at higher energies. These alternate correction factors are not included in 10CFR20 at present.

e) The diamond detector had a response characteristic comparable to a good ion chamber and may have some significant operational advantages.

f) GM counters operated without their beta shield at low energies may show a significant over-response.

g) Scintillator-based instruments should not be used in applications where accurate measurements are needed due to their extremely strong variation in response with energy.

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This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

Table 5.

Measurement Error Ranges for GM Counters and Ion Chambers in Response to Three Different Spectra for Different Measurement Assumptions (Cases c-g).

Instrument		Relative Response Accuracy - Range of Values				
		Case c	Case d	Case e	Case f	Case g
	Meas. →	rem = R	C_x @ 1 gm/cm^2	C_x @ 1 gm/cm^2	rem = R	C_x @ 0.007 gm/cm^2
	Dose →	C_x @ 1 gm/cm^2	C_x @ 1 gm/cm^2	C_x #ICRP26 Weighted	C_x #ICRP26 Weighted	C_x @ 1 gm/cm^2
GM Counters						
Low Energy (Spectrum 1)		0.270 - 6.43	0.381 - 8.98	1.140 - 27.90	0.812 - 19.30	0.391 - 9.29
High Energy (Spectrum 2)		0.290 - 1.43	0.308 - 1.49	0.487 - 2.36	0.468 - 2.27	0.309 - 1.49
Medium Energy (Spectrum 3)		0.290 - 1.36	0.296 - 1.43	0.480 - 2.31	0.461 - 2.20	0.298 - 1.43
Ion Chambers						
Low Energy (Spectrum 1)		0.330 - 2.95	0.461 - 4.05	1.38 - 12.16	0.983 - 8.86	0.473 - 4.21
High Energy (Spectrum 2)		0.693 - 1.75	0.726 - 1.83	1.15 - 2.88	1.09 - 2.76	0.730 - 1.83
Medium Energy (Spectrum 3)		0.710 - 1.75	0.746 - 1.83	1.21 - 2.96	1.15 - 2.82	0.750 - 1.83

Table 6.

Measurement Errors for Specific Instruments in Response to Three Different Spectra for Different Measurement Assumptions (Case c-g).

Instrument		Relative Response Accuracy - Range of Values				
		Case c	Case d	Case e	Case f	Case g
	Meas. →	rem = R	C_x @ 1 gm/cm^2	C_x @ 1 gm/cm^2	rem ≅ R	C_x @ 0.007 gm/cm^2
	Dose →	C_x @ 1 gm/cm^2	C_x @ 1 gm/cm^2	C_x #ICRP26 Weighted	C_x #ICRP26 Weighted	C_x @ 1 gm/cm^2
Victoreen 471 Ion Chamber						
Low Energy (Spectrum 1)		0.836	1.065	3.198	2.509	1.149
High Energy (Spectrum 2)		0.963	1.003	1.586	1.522	1.005
Medium Energy (Spectrum 3)		0.960	1.005	1.625	1.554	1.006
Eberline PRM-7 Scintillator						
Low Energy (Spectrum 1)		7.02	9.82	29.50	21.09	10.14
High Energy (Spectrum 2)		0.624	0.737	1.16	0.986	0.743
Medium Energy (Spectrum 3)		0.818	0.963	1.56	1.32	0.968
Diamond Detector						
Low Energy (Spectrum 1)		0.718	0.979	2.94	0.216	1.02
High Energy (Spectrum 2)		0.961	1.00	1.59	1.52	1.01
Medium Energy (Spectrum 3)		0.971	1.02	1.65	1.57	1.02
TLD (LiF)						
Low Energy (Spectrum 1)		0.787	1.036	3.11	2.36	1.09
High Energy (Spectrum 2)		0.956	0.996	1.57	1.51	0.997
Medium Energy (Spectrum 3)		0.951	0.994	1.61	1.54	0.995